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Atmos. Chem. Phys. Discuss., 8, 2849–2862, 2008
www.atmos-chem-phys-discuss.net/8/2849/2008/

Atmospheric Chemistry and Physics Discussions

Correlation between equatorial Kelvin waves and the occurrence of extremely thin ice clouds at the tropical tropopause

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Received: 7 December 2007 – Accepted: 8 January 2008 – Published: 13 February 2008

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Abstract

A number of field-campaigns in the tropics have been conducted in the recent years with two different LIDAR systems at Paramaribo in Suriname (5.8° N, 55.2° W). The lidars detect particles in the atmosphere with high vertical and temporal resolution and are capable of detecting extremely thin cloud layers which frequently occur in the tropical tropopause layer (TTL). Radiosonde as well as operational ECMWF analysis show that temperature anomalies caused by equatorial Kelvin waves propagate downward, well below the cold point tropopause (CPT). We find a clear correlation between the temperature anomalies introduced by these waves and the occurrence of thin cirrus in the TTL. In particular we found that extremely thin ice clouds form regularly where cold anomalies shift the tropopause to high altitudes. This finding suggests an influence of Kelvin wave activity on the dehydration in the TTL and thus on the global stratospheric water vapour concentration.

1 Introduction

The tropical tropopause layer (TTL) is the layer between the level of zero net radiative heating which is found typically around 15 km (Gettelman et al., 2004) and the cold point tropopause (CPT) at 17 to 18 km. This layer is characterized by slow ascent and forms the source region for the stratospheric Brewer-Dobson circulation. Thin laminar ice clouds are frequently observed in the TTL (e.g. Winker and Trepte, 1998; Peter et al., 2003; Immler and Schrems, 2002). The way these clouds form and their ability of dehydrating the ascending air are of crucial importance for the water vapour budget of the stratosphere. While formation of clouds by direct injection from convective systems into the TTL will most likely moisten the air by evapouration of the particles (Nielsen et al., 2007), in situ formation of clouds in slowly ascending air will almost always lead to dehydration (Jensen and Pfister, 2004).

On the basis of observational data obtained in Paramaribo, Suriname we showed recently that cirrus clouds form in situ and effectively dehydrate the air as it ascends to the stratosphere (Immler et al., 2007, I07 hereafter). In accordance to modeling studies presented by Bonazzola and Haynes (2004); Jensen and Pfister (2004); Fueglistaler et al. (2005), our observations suggest that air is dried to the saturation vapour pressure of the minimum temperature that the air parcel experiences on its way to the stratosphere.

Boehm and Verlinde (2000) showed that the temperature at the tropical tropopause is significantly influenced by equatorial Kelvin waves and that the occurrence of cirrus in the upper tropical troposphere is related to the cold anomalies of these waves. Based on observations by a micropulse lidar (MPL) they found that cirrus clouds occur primarily around 15–16 km and below and thus assumed that at higher altitudes moisture is not sufficient to form clouds. Furthermore, in a detailed analysis of data from the same instrument Comstock et al. (2002) demonstrated that cirrus occurrence at altitudes above 15 km do not coincide with negative temperature anomalies.

During an aircraft campaign in the Indian ocean Peter et al. (2003) observed extremely thin ice clouds near the tropical tropopause (Ultrathin Tropical Tropopause Clouds, UTTC) "which can neither be observed by ground-based lidar nor by the pilot of the high-flying aircraft". They suggest that these clouds are sustained by a subtle balance between up-welling of the air and sedimentation of the ice particles (Luo et al., 2003).

In September–October 2004 and in October 2006, we have conducted field campaigns at Paramaribo, Suriname (5.8° N, 55.2° W) with high performance ground-based lidar systems which are capable of detecting extremely thin ice clouds (Immler et al., 2007). In this paper we demonstrate a strong link between the cold phase of Kelvin waves and the occurrence of thin ice clouds near the tropical tropopause. Thus, we provide evidence that Kelvin waves play an important role for the formation of these clouds and may work like a "dehydration pump" that dries the lowermost tropical stratosphere (Fujiwara et al., 2001).

2 Observational methods

In the frame of the European project STAR (Support for Tropical Atmospheric Research), the Mobile Aerosol Raman Lidar (MARL) was set up at the meteorological service of Suriname (MDS) at Paramaribo in September 2004 and operated from 27 September 2004 to 16 December 2004 (STAR period) which corresponds to the local long dry season. Further campaigns followed in the short spring dry season of 2005 and 2006. In September 2006, MARL was replaced by the newly built Compact Cloud and Aerosol Lidar (ComCAL) (Immler et al., 2006). ComCAL performs TTL cirrus observation from 19 September to 29 November 2006 (ACLIT (Aerosol and Cloud measurements by LIdar in the Tropics) period). While the ComCAL system was operated during day and night, the MARL was not operated between 09:00 and 16:00 local time because of its very high sensitivity and too intense background light. Both lidar systems are capable of detecting extremely thin tropical cirrus clouds (ETTCi) near the tropopause. Further details on the lidar data analysis and cloud detection methods are found in I07.

Informations on the meteorological conditions in the TTL were obtained by special daily Vaisala-RS80 radiosoundings at Paramaribo during the STAR period. During the ACLIT campaign, only 2–3 radiosondes were launched per week, which is insufficient to resolve Kelvin waves properly. Therefore we use operational analysis from the European Centre for Medium range Weather Forecasts (opECMWF).

In I07, a newly developed trajectory code (AWI trajectory code) was discussed which uses ECMWF horizontal winds and calculates vertical velocities explicitly from radiative heating rates in the TTL and the stratosphere. It was shown that it is very useful for investigating transport processes in the upper part of the TTL (Krüger et al., 2007). This trajectory model is used here as well.

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3 Results and discussion

Figure 1a and Fig. 2a show cloud observations by the MARL and ComCAL lidar systems during September-October 2004 and October 2006, respectively. Cirrus in the uppermost troposphere was very ubiquitous. Striking is the downward trend of the cloud top heights which seem to descend with time on a scale of several days before new clouds appear at higher altitudes. This behavior indicates the influence of synoptic-scale disturbances on the cloud occurrence.

Figure 1b shows temperature anomalies retrieved from radiosonde data. These were calculated using the mean temperature profile of the period (Fig. 4a, dashed line). Figure 1b shows downward propagating warm and cold anomalies with a periodicity of 4 to 5 days (5 wave cycles in 19 days). These are typical features of equatorial Kelvin waves with a zonal wavenumber of 4 as they were described by Holton et al. (2001). These waves are excited by remote convective systems and propagate eastward around the globe close to the equator. Figure 1b shows clearly that the waves are propagating in the TTL and the lower stratosphere across the cold point tropopause (dashed red line). Note that the group velocity, i.e. the energy of these waves, propagate upward, while the warm and cold phases appear to propagate downwards. The waves extend approximately down to the level of the upper tropospheric inversion (UTI). The latter is a weak inversion layer which is regularly found in tropical temperature profiles approximately 1–2 km below the temperature minimum and marks the lower boundary of the TTL (Immler and Schrems, 2002; Fujiwara et al., 2003).

The temperature changes at the CPT induced by the waves reach amplitudes of up to 8 K with typical values of 2–3 K. The cold phase of the Kelvin waves is marked by arrows in Fig. 1b and are copied into Fig. 1a in order to show the correlation between the cold temperature anomalies and the occurrence of cirrus. The black crosses indicate the top altitudes of clouds detected by the lidar in Paramaribo. Clearly, clouds in the TTL occur almost exclusively in regions with a cold anomaly, while warm anomalies inhibit cloud formation.

For the ACLIT period in October 2006 the temperature anomalies were retrieved from the high vertical-resolution version of the opECMWF analyses with 91 model levelas (Fig. 2b). We see the same downward propagating features that are typical for equatorial Kelvin waves. Again, there is a strong correlation between the cold phases in the TTL and the occurrence of cirrus.

The CPT follows the descending cold anomalies to some extent until it rises rapidly when a new cold anomaly reaches an altitude of about 17–18 km (Fig. 1b and Fig. 2b). At this newly formed CPT we find regularly extremely thin cirrus clouds. The occurrence of these thin clouds are marked with white circles in Figs. 1a and 2a.

Figure 3 is a compilation of the temperature anomalies as shown in Figs. 1b and 2b averaged over the cloud range for each cloud event detected by the lidar during the entire campaign. Clouds above 15.5 km occur almost exclusively in cold anomalies, proving that thin ice clouds that occur near the tropical tropopause are closely correlated with Kelvin waves. A "stratospheric influence" on cloud formation in the TTL (below 15–16 km) was demonstrated by Boehm and Verlinde (2000) and Comstock et al. (2002). However, in contrast to their findings, we find this correlation to increase with cloud top altitude. The reason for this discrepancy may be that our lidar systems are sensitive to extremely thin clouds while the one used in these studies is not.

In order to show a detailed case of an extremely thin cloud occurring at the CPT, the temperature and temperature anomaly profiles are plotted in Fig. 4a which were measured on 11 October 2004, 08:26 UT. The temperature profile has a double tropopause structure which is typical for the situation when the cold phase of Kelvin waves approaches towards the tropopause region. The upper temperature minimum at 17.2 km altitude is clearly related to a downward propagating cold anomaly that reaches the TTL at the time of the observation (see the vertical gray arrow in Fig. 1b). The temperature profile in Fig. 4 shows a lower lapse rate tropopause at about 16.5 km altitude. The thermal structure of the TTL is obviously strongly influenced by the Kelvin wave and so is the existence of ice clouds, in particular the upper layer at the temperature minimum (Fig. 4, middle).

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This relation is investigated in more detail with the help of backward trajectories which were calculated with the AWI trajectory code that was used for our previous study in I07 and Krüger et al. (2007). The thin red line in Fig. 4 (right) depicts the history of the potential temperature of the air parcel that contains the upper cloud of Fig. 4b. This air was transported into the TTL about 8 days before. In the TTL the air slowly ascents, while the temperature (thick lines) goes up and down. Within the last couple of days the air was cooled by about 5 K (see the thick red line) which is presumably caused by the Kelvin wave. This air parcel has cooled to temperatures below the radiative equilibrium and is therefore radiatively heated which is reflected in an increasing slope of the potential temperature (thin red line). This heating caused the air parcel to rise faster and thereby to cool adiabatically even more. The temperature anomaly of almost 8 K (left, green line, at CPT) was brought about by the joint action of the Kelvin wave and the radiatively driven ascent.

Our observations are restricted to areas outside of deep convection by the nature of the lidar measurements which can only be performed during the absence of low and mid level clouds. Therefore, our conclusions apply only to regions which are not directly affected by deep convection. However most of the vertical transport from the troposphere to the stratosphere is obviously not directly related to convection : We have repeatedly observed high coverage with thin cirrus in the TTL detached from deep convection (I07, Immler and Schrems, 2002) which seems to be the case for the great majority of TTL cirrus. Satellite obseravtions demonstrated that 90% of the tenuous cirrus near the tropopause is located away from deep convection (Massie et al., 2002).

Left: Profiles of temperature measured by a radiosonde launched on 11 November 2004, 10:16 UT (red), temperature from operational ECMWF data on the same day but at 06:00 UT (gray), mean temperature during the STAR period (dashed), and temperature anomaly (green). Middle: Lidar backscatter profile measured between 08:07 and 08:26 UT. Right: Backward and forward trajectories calculated from 11 October 2004, 06:00 UT from three different levels. Thick lines show the temperature history of the air parcels, and thin lines show their potential temperature history. The green lines refer to the air parcel containing the cloud around 15.8 km, while the red lines refer to the air parcel containing a very thin cloud at about 17 km.

4 Conclusions

The correlation of cloud observations by lidar with temperature anomalies determined from radiosonde measurements or opECMWF analysis demonstrates that cirrus occurrence in the tropical tropopause region is closely related to equatorial Kelvin waves. The downward propagating cold anomalies obviously provide favorable synoptic-scale conditions in the TTL for enforced ascent and adiabatic cooling of air parcels followed by ice particle formation and dehydration.

As Boehm and Verlinde (2000) have pointed out, the temperature anomalies caused by waves modulate the thermal structure of the tropical tropopause region and support the creation of a very cold secondary tropopause around 17 km above the conventional lapse rate tropopause (or UTI) around 15 km. However, they did not establish a correlation to the formation of clouds at the upper part of the TTL probably due to a limited ability of their instrument to detect the extremely tenuous clouds. Our observations demonstrate that extremely thin clouds occur regularly around 17 to 18 km when a particularly high tropopause coincides with the cold phase of a Kelvin wave.

These observations suggest that the level of water vapour flux into the stratosphere depends on the degree of Kelvin wave activity, with higher wave activity leading to stronger dehydration and a drier lowermost stratosphere in the tropics. Should the intensity of Kelvin wave activity change in a changing climate, this could link anthropogenic climate forcings with stratospheric water vapour levels, with all its global implications.

Acknowledgements. We like to thank I. Beninga, D. Kaiser, and R. Maurer for operating the lidar systems in Paramaribo, as well as C. Becker and the staff from the Meteorologische Dienst Suriname for their great support. We thank the ECMWF for giving access to their data. This work was supported by the EU projects STAR, ACCENT, and SCOUT-O3 as well as by the Helmholtz foundation within the project PEP.

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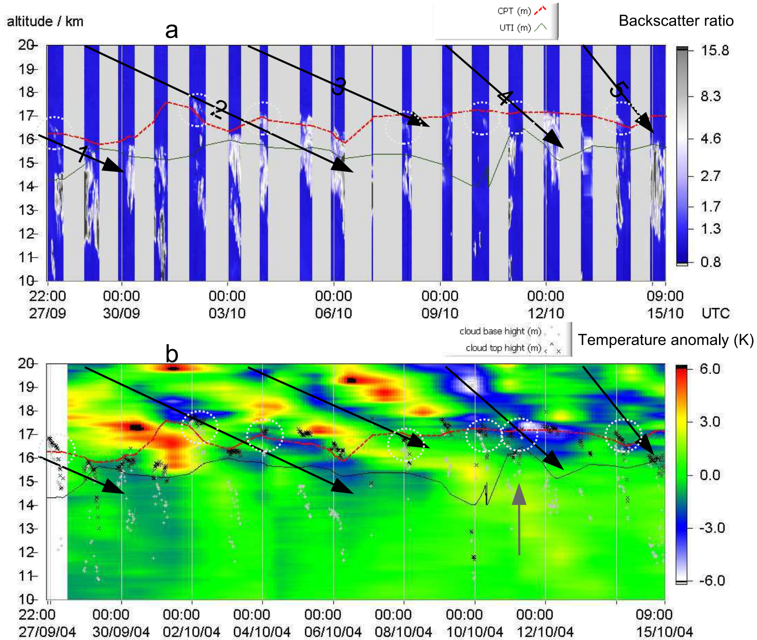

Fig. 1. (a) Lidar observations of cirrus clouds at Paramaribo from 27 September to 15 October 2004. Plotted is the backscatter ratio (i.e., observed total backscatter versus calculated pure molecular backscatter) as a function of time and altitude. Values greater than 1.5 indicate the presence of clouds. **(b)** Temperature anomalies calculated from radiosonde data during the same period as in (a). The red lines for both panels show the location of the cold point tropopause (CPT), and the black lines show the location of the upper tropospheric inversion (UTI). Slanted arrows in both panels indicate the major cold anomalies. White circles in (a) indicate extremely thin cirrus at the CPT (see text). In (b), black crosses indicate the upper edge of cirrus clouds observed by the lidar, and gray crosses indicate the lower edge. The vertical gray arrow in (b) corresponds to the case in Fig. 4.

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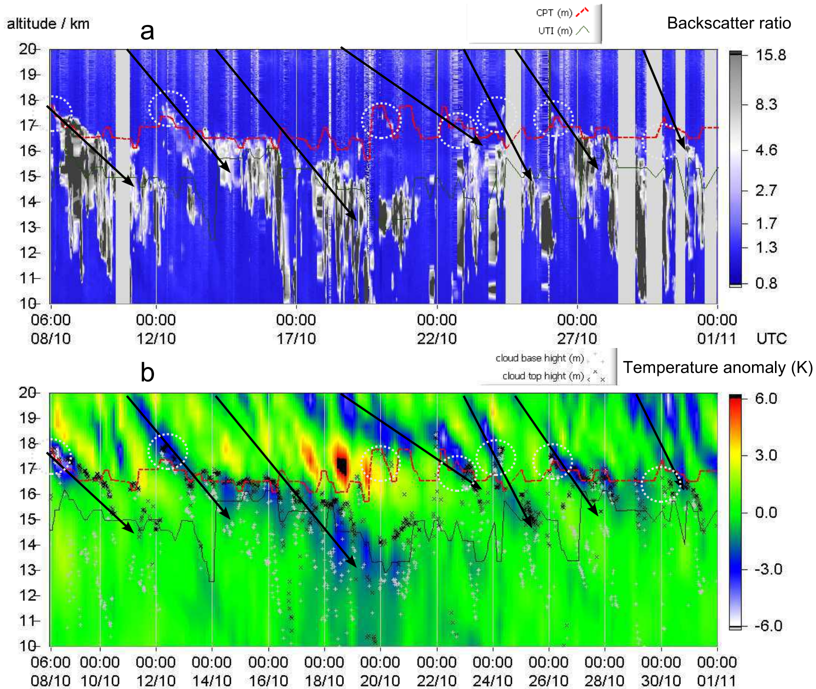

Fig. 2. Same as Fig. 1 but for the ACLIT period, from 8 October to 1 November 2006. The temperature anomalies in **(b)** are retrieved from opECMWF data at 6.0° N, 56° W.

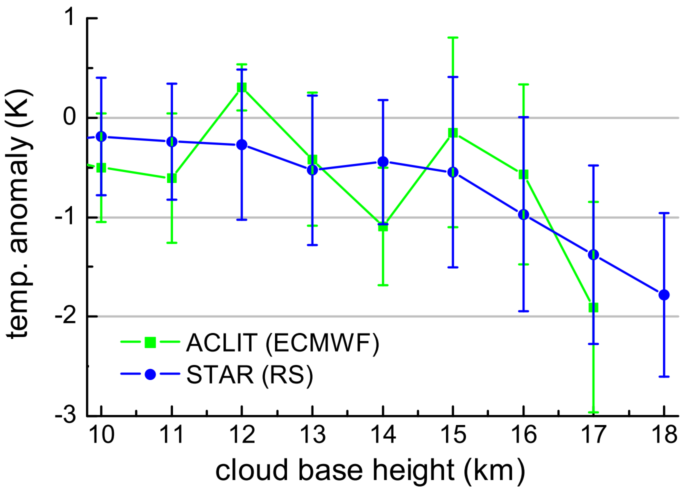

Fig. 3. Mean in-cloud temperature anomaly as a function of cloud base height retrieved from lidar and collocated radiosonde or operational ECMWF data for the STAR (blue) and ACLIT (green) periods, respectively. The error bars mark the variability (1σ) within each 1 km altitude bin.

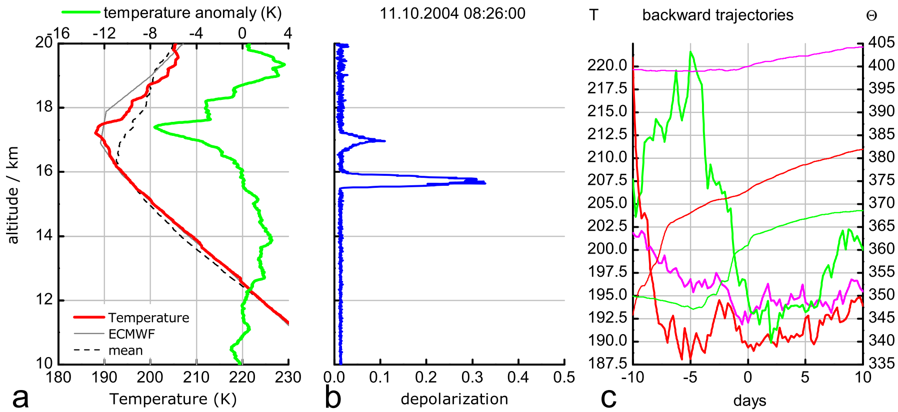

Fig. 4. Left: Profiles of temperature measured by a radiosonde launched on 11 November 2004, 10:16 UT (red), temperature from operational ECMWF data on the same day but at 06:00 UT (gray), mean temperature during the STAR period (dashed), and temperature anomaly (green). Middle: Lidar backscatter profile measured between 08:07 and 08:26 UT. Right: Backward and forward trajectories calculated from 11 October 2004 06:00 UT from three different levels. Thick lines show the temperature history of the air parcels, and thin lines show their potential temperature history. The green lines refer to the air parcel containing the cloud around 15.8 km, while the red lines refer to the air parcel containing a very thin cloud at about 17 km.